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Extracting strong phase and CP violation in D decays by using quantum correlations in $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(K\pi)$ and $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$

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In this paper, we exploit the angular and quantum correlations in the $D\bar{D}$ pairs produced through the decay of the $\psi(3770)$ resonance in a charm factory to investigate CP-violation in two different ways. We consider the case of $\psi(3770) \to D\bar{D} \to (V_1V_2)(K\pi)$ decays, which provide a new way to measure the strong phase difference δ between Cabibbo-favored and doubly-Cabibbo suppressed D decays required in the determination of the CKM angle γ. We also build CP-violating observables in $\psi(3770) \to D\bar{D} \to (V_1V_2)(V_3V_4)$ to isolate specific new physics effects in the charm sector. Neglecting the systematics, we give a first rough estimate of the sensitivities of these measurements at BES-III with an integrated luminosity of 20 fb^{-1} at $\psi(3770)$ peak and at a future super τ-charm factory with a luminosity of 10^{35} cm^{-2}s^{-1}

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1. Introduction

In the framework of standard model (SM), CP violation in the charm sector is very small, thus any significant amount of CP violation will be a clean signal of new physics (NP). There have been much papers on this. In our work, we will fully exploit $D \to VV$ modes which exhibit rather large branching ratios, of similar size with respect to PP (P denote pseudoscalar meson) or VP (V denote vector meson) modes, and provide further new observables. These points have not been detailed so far and can be verified at BES-III or other charm factories.

2. Correlated D decay

$D^0\overline{D}^0$ pair produced in $\psi(3770)$ is in antisymmetric coherent state which can be written as

$$|(D\bar{D})_{L=1}\rangle = \frac{-|D_1\rangle|D_2\rangle + |D_2\rangle|D_1\rangle}{\sqrt{2}}. \tag{2.1}$$

For correlated D decays, one can in principle consider the following different situations,

- $(PP)+(PP), (PP)+(VP), (VP)+(VP)$: the only available observable is the branching ratio, since the partial waves and helicities are all fixed by angular momentum conservation.
- $(PP)+(VV), (VP)+(VV)$: (VV) can have three helicity states, and thus there are new angular observables. This can be exploited for $(PP) = K\pi$ in connection with the measurement of the CKM angle γ.
- $(VV)+(VV)$: this will be studied with an interest in new observables for CP-violation.

Now we list the decay chains, $\psi \to D_1D_2,\ D_1 \to V_1V_2,\ D_2 \to K\pi$ for γ measurement and $\psi \to D_1D_2,\ D_1 \to V_1V_2,\ D_2 \to V_3V_4$ for CP violation, with all the vector mesons sequential decaying to their pseudoscalars.

Next we will construct the observables from the differential decay width expressed in helicity angle and helicity amplitudes corresponding to these two decay chains.

3. Observables and potential at charm factories

3.1 For γ measurement

Introducing $r \cdot e^{i\delta} = \frac{\langle K^-\pi^+|\overline{D}_0\rangle}{\langle K^-\pi^+|D_0\rangle}$, the differential decay width can be written as [1]

$$\begin{aligned} d\Gamma_{2V} \;=\; & \frac{9}{4\pi} d(\cos\theta_{V_1}) d(\cos\theta_{V_2}) d\Phi \times |A^{\psi V_1 V_2}|^2 |A^{D^0\to K\pi}|^2 && (3.1)\\ & \times\Big[\cos^2\theta_{V_1}\cos^2\theta_{V_2}|A_0^{D^0\to V_1V_2}|^2(1+2r\cos\delta+r^2) \\ & \quad +\frac{1}{2}\sin^2\theta_{V_1}\sin^2\theta_{V_2}\cos^2\Phi|A_{||}^{D^0\to V_1V_2}|^2(1+2r\cos\delta+r^2) \\ & \quad -\sqrt{2}\cos\theta_{V_1}\sin\theta_{V_1}\cos\theta_{V_2}\sin\theta_{V_2}\cos\Phi Re[A_0^{D^0\to V_1V_2}(A_{||}^{D^0\to V_1V_2})^*](1+2r\cos\delta+r^2) \\ & \quad +\cdots\Big] && (3.2) \end{aligned}$$

In the above expression, we see that,

- The branching ratio only depends on the three amplitude combinations

$$M_0 = A_0(1+re^{i\delta}), \quad M_{||} = A_{||}(1+re^{i\delta}), \quad M_\perp = A_\perp(1-re^{i\delta}). \tag{3.3}$$

- since δ is small, the sensitivity on sine in addition to cosine (PP case) is expected to improve the final results.

Thus, the above constraint can be improved by exploiting the expected knowledge of polarization of VV modes (single-tag), then the measurement of M_i in the correlated decay (double-tag) may lead to a better result on δ.

The error on $\cos\delta$ is given by [2]

$$\Delta(\cos\delta) \approx \frac{1}{2r\sqrt{N_{K^-\pi^+}}} \approx \frac{\pm 284.5}{\sqrt{N(D^0 \overline{D}^0)}}. \tag{3.4}$$

At BES-III, about 72×10^6 $D^0\overline{D}^0$ pairs can be collected with four years running, which implies an accuracy of about 0.03 for $\cos\delta$, when considering both $K^-\pi^+$ and $K^+\pi^-$ final states. Citing the present average result of $\delta = (26.4^{+9.6}_{-9.9})^\circ$, we can get the error of δ, $\Delta(\delta) = \pm 3.9^\circ$ at BES-III, and $\Delta(\delta) = 0.4^\circ$ at super-τ-charm factory with the luminosity about 100 times improvement than BES-III. At this stage, the results are pure statistics. The true experimental systematics are required to be studied. Here we want to emphasize one thing again, size of other terms (e.g. $\sin\delta$) has not been studied yet and expected to improve the measurement.

3.2 For *CP* violation

If we take the decay chain [3]

$$e^+e^- \to \psi \to D^0\bar{D}^0 \to f_a f_b \tag{3.5}$$

with f_a and f_b CP eigenstates of the same CP-parity, we have

$$CP|\psi\rangle = |\psi\rangle \qquad CP|f_a f_b\rangle = \eta_a \eta_b (-1)^\ell |f_a f_b\rangle = -|f_a f_b\rangle \tag{3.6}$$

since f_a and f_b are in a P wave. Therefore, the decay of ψ into the states of identical *CP* parity is, by itself, a *CP* violating observable. In fact one can obtain the following combined branching ratio with neglecting *CP* violation in $D^0\overline{D}^0$ mixing [4],

$$Br((D^0\bar{D}^0)_{C=-1} \to f_a f_b) = 2Br(D_0 \to f_a)Br(D_0 \to f_b)(|\rho_a - \rho_b|^2 + r_D|1-\rho_a\rho_b|^2) \tag{3.7}$$

with

$$\rho_f = \frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)}, \quad r_D = (x^2+y^2)/2 < 10^{-4} \tag{3.8}$$

Thus, *CP* conservation at the level of the amplitude would require that only two combinations of transversity amplitudes are allowed: $(0,\perp)$ or $(||,\perp)$ since we know the parallel helicity "||" is *CP* even and the perpendicular one "$\perp$" is *CP* odd. Other combinations such as $(0,0)\,(0,||)\,(||,0)\,(||,||)\,(\perp,\perp)$ should be *CP* violating observables. Exploiting orthogonality relationships for Legendre and

Chebyshev polynomials to select specific angular dependence from the whole differential decay width, one can get these *CP* violating observables [1],

$$\int d\Gamma_{4V}\frac{1}{8}(5\cos^2\theta_{V_1}-1)(5\cos^2\theta_{V_2}-1)(5\cos^2\theta_{V_3}-1)(5\cos^2\theta_{V_4}-1)$$
$$=|A^{\psi V_1V_2V_3V_4}|^2|A_0^{D_0\to V_1V_2}|^2|A_0^{D_0\to V_3V_4}|^2\times|\rho^0_{V_1,V_2}-\rho^0_{V_3,V_4}|^2$$
$$\int d\Gamma_{4V}\frac{1}{32}(5\cos^2\theta_{V_1}-3)(5\cos^2\theta_{V_2}-3)(5\cos^2\theta_{V_3}-3)(5\cos^2\theta_{V_4}-3)$$
$$\cdot(4\cos^2\Phi-1)(4\cos^2\Psi-1)$$
$$=|A^{\psi V_1V_2V_3V_4}|^2|A_{||}^{D_0\to V_1V_2}|^2|A_{||}^{D_0\to V_3V_4}|^2\times|\rho^{||}_{V_1,V_2}-\rho^{||}_{V_3,V_4}|^2$$
$$\ldots$$

Note that this projection yields CP violating observables without performing a full angular analysis.

If we parameterize ρ_f as $\rho_f=\eta_f(1+\delta_f)e^{i\alpha_f}$ (δ_f is CP violation in decay and can be negligible.), we can get, as an illustrative example, the branching ratio for the the most promising channel $\rho^0\rho^0/\bar{K}^{*0}\rho^0$ which has large branching ratio among the *CP* eigenstates,

$$Br((D^0\bar{D}^0)_{C=-1}\to\rho^0\rho^0,\bar{K}^{*0}\rho^0)\Big|^{CPV}_{(0,||)}\simeq 8Br^0(D^0\to\rho^0\rho^0)\cdot Br^{||}(D^0\to\bar{K}^{*0}\rho^0)\sin^2\frac{\alpha_a-\alpha_b}{2}. \quad (3.9)$$

"0" and "‖" in the superscript means the corresponding fraction. Assuming no *CP* violating signal events are observed we have the upper limit, $|\alpha_a-\alpha_b|<4.4^\circ$ at 90%-C.L. at BESIII and $|\alpha_a-\alpha_b|<0.5^\circ$ at 90%-C.L. at super-τ-charm factory. Its branching fraction will be estimated to the level of less than 10^{-7} if there is no CP violating events at BES-III. At super τ-charm factory it would be reduced by one order.

4. conclusion

In the case of CP-tagged $D\to K\pi$ decays, we expect the determination of the error on δ can be improved by taking into account the dependence of the full angular decay width to the sine of the strong phase. In the case of $\psi(3770)\to D^0\bar{D}^0\to(V_1V_2)(V_3V_4)$, CP-violating observables can be constructed and phase differences are discussed. To conclude, we say again that a further careful study of experimental systematics is required since they presumably dominate the quoted uncertainty here.

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